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Deformations of flexible and foldable electro-active composite structures

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ABSTRACT

This paper presents numerical analyses of elastic and viscoelastic smart flexible and foldable composite structures under electric field actuation. The studied composites comprise of multiple distributed piezoelectric patches bonded to the surfaces of in-active thin planar structures (substrates). Upon applications of electric field input, the planar structures can undergo three-dimensional large rotational deformations while their strains and stretches remain relatively small. A nonlinear time-dependent electro-mechanical coupling relation for the piezoelectric patches is considered to simulate more precisely response of piezoelectric materials when subjected to large magnitude of electric field. Co-rotational Lagrangian finite element approach is used for solving the governing equations of the deformations of flexible and foldable electro-active composite structures. Various three-dimensional shape changes of originally planar structures are achieved with different arrangements of integrated patches and subjected to different magnitude of electric fields. The effect of viscoelastic substrates and time-dependent electro-mechanical coupling of piezoelectric materials on the deformed shapes is also studied. This analysis can help designers in simulating desired deformed shapes and determining external stimuli to be prescribed prior to fabricating smart and flexible composites.

1. Introduction

Structures integrated with smart materials, such as shape memory, magnetostrictive and piezoelectric materials, known as smart structures, are appealing for the development of new generation of autonomous systems with sensing and adaptation ability. Smart structures that are lightweight, flexible and deformable into various configurations find many applications in aerospace industry, biomedicine and robotics. Examples of applications are morphing wings, micro air vehicles, soft robots, artificial skins, vascular stents, and electronic packaging systems. Flexible structures are macroscopically compliant, which are often in the forms of long filaments and thin sheets that can be deformed into various geometrical shapes. Depending on the geometrical shapes considered, flexible structures can experience relatively small strains while undergoing large rotations [1,2]. In this work, we study the deformation of smart flexible planar structures with integrated thin piezoelectric patches, in which deformations and shape changes are controlled by electric field inputs prescribed to the piezoelectric actuators. We consider two piezoelectric materials for the patches, which are, lead zirconate titanate (PZT) ceramics and active fiber composites (AFC). When piezoelectric ceramics based actuators are considered, it limits the strains in the flexible structures and large deformations in such structures are predominantly due to large rotations. One solution to enhance deformations in piezoelectric ceramics based actuators is to form active fiber composites (AFC) which have PZT fibers embedded in a polymeric matrix. AFC was originally proposed by Ben and Hagood [3].

Flexible structures are typically undergoing large displacements (large stretch and/or large rotation) when subjected to external stimuli, whose motion cannot be sufficiently described based on linearized kinematics. There have been several studies on analyzing three-dimensional deformation of thin plates and shells with nonlinear geometries [4–6] mainly under mechanical loads. Moderate and large deformations of plates are governed by coupled nonlinear differential equations for which analytical solutions are available only for a few cases involving simple geometries and loading conditions [7]. There have been limited studies on analyzing nonlinear deformations of plates and shells integrated with piezoelectric actuator. Chen and Chen [8] studied piezoelectric layered-plates by adopting von Karman theory and using finite difference method in order to obtain solutions to the governing equations for moderate deformations, e.g. von Karman strains. Xue et al. [9] solved nonlinear partial differential equations for moderate deflections of thin plates made of piezomagnetic and piezoelectric materials under transverse mechanical loads by using Bubnov–Galerkin method.

One of the commonly used numerical techniques for solving large deformations of plates and shells is finite element method

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(FEM). In FE analysis with geometric nonlinearity, three Lagrangian kinematic descriptions have been formulated: (a) total Lagrangian (TL), (b) updated Lagrangian (UL) and (c) co-rotational (CR). For the TL approach, the governing equations are written with respect to the original configuration of the body while for the UL method, the reference configuration is updated at each step or increment, and the equations are formulated with respect to the equilibrated configuration from the previous step. The CR description is based on a separation of rigid body displacements from the deformational displacements, which can be used for analyzing structures undergoing large deformation mainly due to rotations while the strains remain relatively small. In the CR method, the deformational component is typically formed based on small strain measures, although other general strain measures are also possible. The governing equations are expressed with respect to the current configuration obtained from the rigid body motion of the original configuration. The CR formulation was first introduced by Wempner [10] in 1969 and Belytschko et al. [11] in 1973. Since then, it has been adopted by researchers for studying deformation of structures and multi-body systems which often involves large ratio of rigid body motions to total deformation [12–16]. Felippa and Haugen [17] summarized the existing CR formulations and presented a unified theoretical framework for co-rotational finite element (CRFE) in geometrically nonlinear analyses of structures. Recently, by using the CR formulation, triangular flat shell elements were constructed by researchers for nonlinear analysis of shells and plates subjected to small strains and large rotations due to mechanical loads [18–20]. Cai and Atluri [21,22] considered also moderate strains by adopting the von-Karman nonlinear strains in the rotated element frame. In all of the above studies, the CR formulation has been considered for flexible linear elastic bodies under mechanical loadings. To the best of our knowledge, the CRFE method has not been used for studying deformations in flexible elastic as well as viscoelastic composite plates/shells actuated by non-mechanical stimuli.

In actuation applications, it is often necessary to apply high electric field inputs to the piezoelectric components in order to obtain large deformations. When subjected to high electric fields, the piezoelectric materials often experience nonlinear electro-mechanical responses. Tiersten [23] was among researchers who studied nonlinear electro-mechanical behaviors of polarized piezoelectric ceramics. He formulated an electro-mechanical constitutive model by considering higher order terms of the electric field in order to describe the nonlinear electro-mechanical coupling behavior of piezoelectric ceramics. A limited number of studies have considered nonlinear electro-mechanical response of piezoelectric materials due to large electric fields [24–26], but for small deformations. Mollayousef [27] and Ben Atitallah et al. [28,29] have studied material characterization of AFC under a wider range of electro-mechanical inputs. Mollayousef used a unit cell approach to characterize the electro-mechanical properties of AFC. Ben Atitallah et al. measured the material properties of AFCs and showed nonlinear time and temperature dependent response of the composite under high temperatures and different strain rates as well as high electric voltages. Tajeddini et al. [30] modeled the relaxation behaviors of AFCs and predicted the creep response of the material under different temperatures and stress levels with a quasi linear viscoelastic (QLV) approach.

In many flexible structures, polymers are widely used for the substrate because of their capability in undergoing large deformations and they are generally lightweight. One of the prominent characteristics of polymers is their viscoelastic behavior. It might be necessary to consider the time-dependent behaviors in the viscoelastic polymeric structures when non-mechanical stimuli are prescribed in order to obtain shape changes. In this study, 3D deformations of smart composite structures having polymeric substrates integrated with piezoelectric patches undergoing large deformations are studied. Co-rotational finite element (CRFE) method is used for numerically solving the equations that govern the deformations of the electro-active composites. Both linear elastic and linear viscoelastic behaviors are considered for the substrates and patches. Nonlinear time-dependent electro-mechanical constitutive equation is considered for the active piezoelectric materials. The numerical results of the deformations and shape changes of smart composite structures are presented. The manuscript is organized as follows. Section 2 presents general governing equations of the nonlinear deformations in electro-active composites. Both piezoelectric ceramics and AFCs are considered as actuators. Section 3 discusses CRFE method for nonlinear structural analysis. Section 4 discussed the CRFE method for the electro-active composite plates followed by numerical analyses of composites plates under various boundary conditions. The study is wrapped up in Section 5.

2. Governing equations of the nonlinear deformations in electro-active composite plates

2.1. Piezoelectric ceramic actuators on viscoelastic substrates

The undeformed structure is considered in the shape of slender flat planar structures which can undergo 3D shape changes. Multiple patches with arbitrary arrangement can be bonded to the top and bottom surfaces of the substrate symmetrically with respect to the middle plane of the plate. It is assumed that the patches are perfectly bonded to the plates. The structure is assumed to have a uniform thickness. Dimitriadis et al. [31] calculated the bending load induced to an elastic plate by a pair of electrically stimulated homogeneous piezoelectric patches bonded perfectly on its top and bottom. For the elastic plates, we follow a similar approach and present the formulation for more general case where the piezoelectric patches are thin and orthotropic. Then, we take into account time-dependent material properties for the substrate and adopt the Laplace transformed method for solving governing equations in case of viscoelastic substrates are considered.

Consider a differential plate element with thickness $2h$ having integrated actuators at the top and bottom faces each with thickness t as shown in Fig. 1. Since the patches are assumed perfectly bonded to the homogeneous substrate, the displacements at the interfaces of the substrate and the piezoelectric patches are continuous; and due to the differences in the elastic moduli of the patches and substrate, stress discontinuities arise at the interfaces. Fig. 1 represents the x-z and y-z stress distributions. The electric stimulus is prescribed on the top and bottom surfaces of the plate such that it induces bending moments to the plate. Therefore, the stress distributions due to the electric stimulus prescribed on the

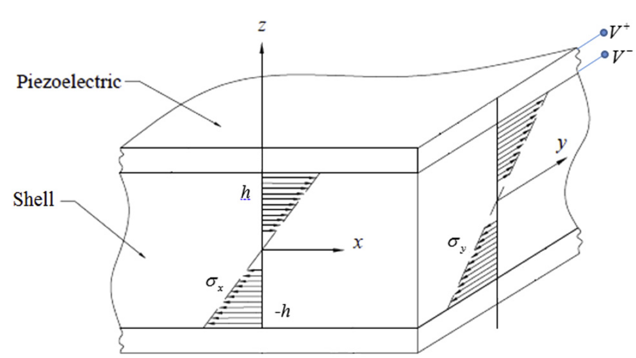

Fig. 1. Stress distribution in the differential plate element due to active piezoelectric.